Data Selection Criteria in Star-Based Monitoring of GOES Imager Visible-Channel Responsivities

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ABSTRACT

Monitoring the responsivities of the visible channels of the operational Geostationary Operational Environmental Satellites (GOES) is an on-going effort at NOAA. Various techniques are being used. In this paper we describe the technique based on the analysis of star signals that are used in the GOES Orbit and Attitude Tracking System (OATS) for satellite attitude and orbit determination. Time series of OATS star observations give information on the degradation of the detectors of a visible channel. Investigations of star data from the past three years have led to several modifications of the method we initially used to calculate the exponential degradation coefficient of a star-signal time series. First we observed that different patterns of detector output versus time result when star images drift across the detector array along different trajectories. We found that certain trajectories should be rejected in the data analysis. We found also that some detector-dependent weighting coefficients used in the OATS analysis tend to scatter the star signals measured by different detectors. We present a set of modifications to our star monitoring algorithms for resolving such problems. Other simple enhancements on the algorithms will also be described. With these modifications, the time series of the star signals show less scatter. This allows for more confidence in the estimated degradation rates and a more realistic statistical analysis on the extent of uncertainty in those rates. The resulting time series and estimated degradation rates for the visible channels of GOES–8 and GOES–10 Imagers will be presented.

Keywords: Calibration, visible, GOES, stars, time series

1. INTRODUCTION

The Geostationary Operational Environmental Satellites (GOES) of NOAA acquire images and radiometric data from the Earth and its atmosphere. Two instruments on the GOES perform such observations, an Imager and a Sounder. Each instrument makes measurements in a number of spectral intervals in the visible and infrared. The Imager has one visible channel whose primary purpose is to provide observation of the Earth in daytime, but which also provides regular observations of stars to help in estimation of the orbit and attitude of the Imager.

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There is no on-board device for calibrating the visible channel of an Imager, because images provided in the visible band were not originally intended for quantitative use. Since the start of the GOES I–M series (1994), however, data from the visible channel have found quantitative application in characterizing properties of the Earth's environment. This has placed requirements for radiometric calibration on that channel. It is particularly useful to conduct long-term monitoring of the responsivity (change in instrument output per unit change in intensity of incoming radiation) of the visible channel. Many stars provide stable and well defined light sources for such monitoring. The star signals computed by the GOES Orbit and Attitude Tracking System (OATS) give information on the responsivity of a visible channel. In 1998, we began systematically retrieving star data archived by the OATS and created time series for the star signals of a group of selected stars, one group for each Imager. For each time series, the decrease over time in the signals was modeled with a decaying exponential function. The constant of decay in the exponential function serves as a measure of the rate of degradation of the responsivity of the visible channel. The results have been placed on the web site www.oso.noaa.gov/goes/goes-calibration/visible-channel.htm.

The fundamental techniques of star-sense monitoring were established by the work of Bremer,et al.[1] Implementation of the star monitoring operation at NOAA commenced in 1998. Over the past three years, research at the National Environmental Satellite, Data, and Information and Service (NESDIS) of NOAA has led to improvements on some of the techniques. The initial trending procedure, which we call Method 1, has been modified into a more restrictive method, which we label as Method 2. Results from both methods are maintained and posted on our web page at regular intervals. (We maintain the results from Method 1 for continuity reasons.) The goal of this paper is to describe the basic components of the two procedures, with emphasis on the transformational steps that lead from the first to the second method. In Section 2, we describe several basic operations in the acquisition of the signals of a star and the subsequent processing of the signals in the OATS. Section 3 is an account of Method 1 and its evolvement into Method 2. In Section 4, we discuss some characteristics of star signals and methods of their acquisition that can place limitations on trending methods we employ. In Section 5, we discuss briefly some current directions of investigation on using stars as sources of vicarious calibration of the visible channels of the GOES Imagers.

2. GOES IMAGER STAR–SENSE OPERATIONS AND GROUND SYSTEM DATA ANALYSIS

Each visible channel of an Imager is equipped with eight detectors. The angular field of view of each detector is 28μrad. The Imager normally scans the Earth. But twice in each hour, it is commanded to view approximately four stars chosen from the star catalog of the OATS. To do this, the field of view of the Imager is slewed to a specified location on space to wait for the transit of a selected star. The image of the star moves across the detectors as the satellite rotates with the earth at 0.25 deg/min. Figure 1 shows the basic geometric configuration of the eight detectors in such a star look. Each detector generates 21,840 measurements (pixels) per second during a star look. To assure a high success rate of the operation, each initial star look is usually followed by a second look, within about 20 seconds. The detector array slews to a position further south and east to take another look at the same star. After the first two looks, further looks may be commanded, but rarely.

The duration of a star look is usually 10–15 seconds, with a maximum allocated time of 64 seconds. The trajectory of the star image at the latitude of the Earth's equator is perpendicular to the axis of the eight detectors. For more northern or southern latitudes, the trajectory is at a small angle from the perpendicular. The greater the absolute value of the latitude, the greater is the angle. Figure 2 and Figure 3 show plots of GOES–8 detector measurements of two stars. We express the magnitude of a signal in Detector Pixel Units (DPUs). One DPU is one count in a detector pixel measurement. For the time scales of the plots, one Detector Time Unit (DTU) is 400/21840 sec., approximately 18.32 milliseconds. The denominator 21840 is the detector data rate described above. The numerator of 400 accounts for a data compression performed on the ground. Each signal in the plots is the sum of 400 consecutive pixel values.

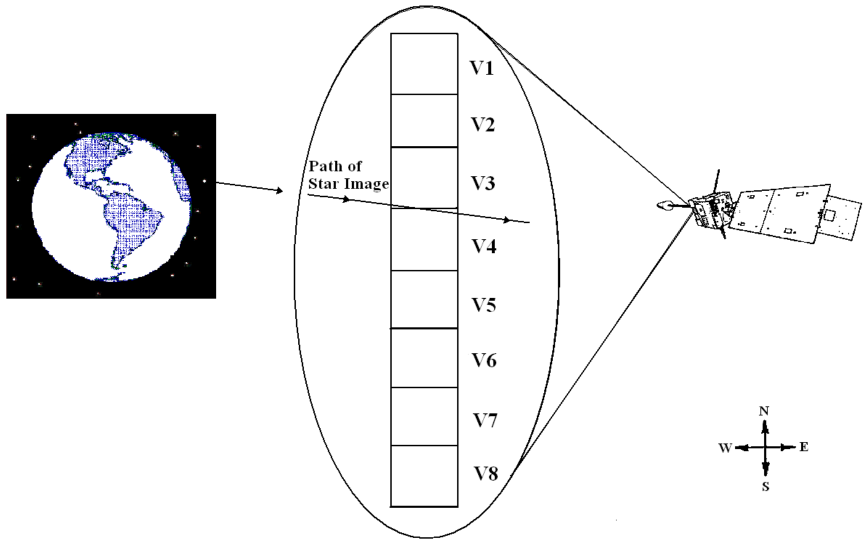

Figure 1. The eight detectors of the visible channel of an Imager conducting a star look.

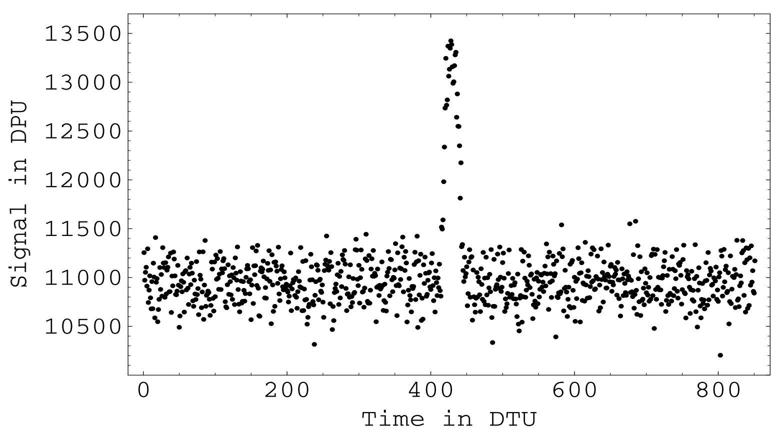

Figure 2. Signals received from Detector 7 of the visible channel of the Imager of GOES–8, in a star look of δ–Eri, conducted on February 3, 2003. One Detector Pixel Unit (one DPU) is one count in a pixel value.

We give here two examples of star looks. In Figure 2 , the Sensor Processing System (SPS) declared detection of the star δ–Eri in Detector 7. The SPS is the ground computer system that carries out calibration and other processing in real time. In this star look, the star transit time is approximately 0.5 sec., based on the estimated 25 consecutive points required to depict the transit. In the next Figure, Figure 3, detections of the star β-Ori were declared for Detector 2 , Detector 3, Detector 4 and Detector 5. The star image moved mostly over Detector 3 and Detector 4, along a path with a mild southward slant. Detector 2 and Detector 5 registered weak star signals from the fringe of the star image.

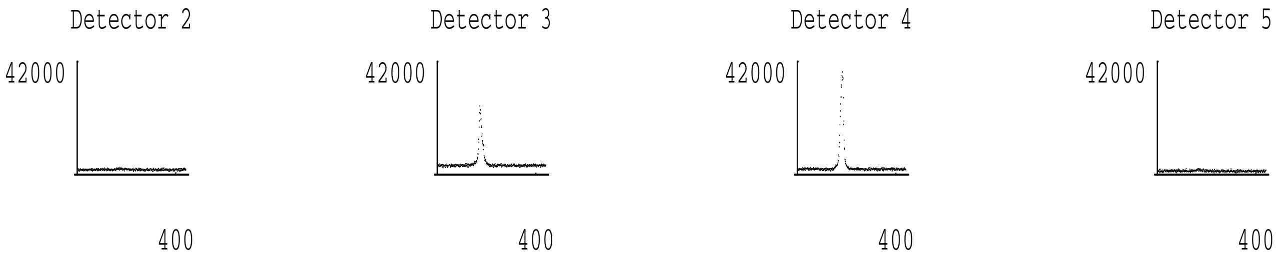

Figure 3. The image of the bright star β-Ori usually spans several detectors. In this crossing on January 27, 2003, signals of the star were detected on four GOES–8 detectors: 2, 3, 4, and 5. Detector 2 and Detector 5 registered weak signals from the fringe of the image. The signal unit is DPU, and the time unit is DTU.

Each star pixel is a 10-bit unsigned integer. The pixel data measured on each detector are transmitted to the SPS. Within the SPS, to reduce the volume of data to be processed, the Sensor Data Interface (SDI) hardware sums every 400 pixels into one superpixel. The number of summands of 400 is an operator adjustable parameter. An example of the eight sequences of superpixels of the star look of Figure 3 is given in Table 1. The Table shows a starting portion of the measurements, a portion containing some peak signals in the star event in Detector 4, and an ending portion.

Table 1. Signals from the eight detectors of the visible channel of GOES–8 Imager in the star look of Figure 3. Each signal entry in the Table is a superpixel – the sum of 400 pixels transmitted from a detector. The signal unit is DPU, and the time unit is DTU.

Index in Detector Time Unit	**Det.** 1	**Det.** 2	**Det.** 3	**Det.** 4	**Det.** 5	**Det.** 6	**Det.** 7	**Det.** 8
1	11362	11491	12177	11179	10934	12086	11800	11005
2	11712	11663	12704	11786	10838	12163	12058	11287
⋮				⋮				⋮
182	11859	11794	21591	36822	10894	12663	12278	11317
183	11904	11729	19267	39057	10922	12490	11733	11409
184	11646	11339	19645	37671	11456	12032	11637	11037
⋮				⋮				⋮
440	11838	11585	12622	11609	11200	11945	12164	11546
441	11714	11348	12693	11385	11276	12005	12010	10953

The detection of star events within the raw superpixels is conducted in the SPS. A plot of the sequence of star superpixels from a detector that has registered a star event typically shows a Gaussian-like profile. In the case of the detection of a star event, SPS algorithms estimate several basic parameters related to the signal profile. The parameters are then passed on to the OATS, where a star signal, denoted by the signal-to-noise ratio (SNR), is determined for this star look. The initial step in the processing in the SPS is to divide each superpixel value with 400 to obtain an average pixel value. For each signal sequence (average pixel values) of a detector where star crossing has been detected, the following parameters are the essential ones estimated by the SPS:

EMS = the average value of a chosen block of signals at the top of the profile.

DMV = the average value of all the signals, including all the higher values due to the transit of the star image.

MFWHM = 1.06 * an estimated FWHM of the star-signal profile.

DURLOOK = the duration of the star look.

These parameters are then sent from the SPS to the OATS. In the following, we describe the OATS processing to estimate the star SNR.

If the star event occurred over only one detector, the star SNR is computed according to the formula

$$\mathrm{SNR} = \left(\mathrm{EMS} - \left(\mathrm{DMV} - \left(\frac{(\mathrm{EMS} - \mathrm{DMV}) * \mathrm{MFWHM}}{\mathrm{DURLOOK}}\right)\right)\right) \left(\frac{\mathrm{GAIN}}{\mathrm{NOISE}}\right) \tag{1}$$

The quantities GAIN and NOISE are detector-dependent constants that reside on the OATS database and are invariant for each satellite. GAIN is a detector–to–detector normalization constant, and NOISE is a typical noise value for the detector. In the calculation of an SNR, if more than one detector registered star crossing, the computed SNR for the star look is the sum of the SNRs computed for each detector that registered a star event. Also only one SNR is designated for each execution the sequence of multiple star looks – the first star look and the second star look, and possibly more. If a star was detected in more than one look, then the composite SNR is the sum of the SNRs from the looks where star crossing was detected.

In the formula (1), the term $\left(\frac{(\mathrm{EMS}-\mathrm{DMV})*\mathrm{MFWHM}}{\mathrm{DURLOOK}}\right)$ is an estimate for the contribution of the star signals to the average value DMV. This expression is an approximation of an exact formula for the case where the star profile is a true Gaussian profile. Thus the term DMV-$\left(\frac{(\mathrm{EMS}-\mathrm{DMV})*\mathrm{MFWHM}}{\mathrm{DURLOOK}}\right)$ is an estimate of the baseline level of the signal. SNR in (1) therefore represents an estimate for the height of the peak signal, weighted with GAIN/NOISE. Without the GAIN/NOISE factor, the magnitude of a signal is expressed in the unit DPU described above.

The procedure we have described here is the basic algorithm of the OATS for computing the SNR for a star look. This computation is actually preceded by several checks to determine whether data from the star look is to be given an SNR value. One kind of star look that is rejected by the OATS is the type where all the detectors that sighted the star did not form a contiguous set.

3. MONITORING THE RESPONSIVITY OF A GOES VISIBLE CHANNEL

In monitoring the responsivity of a visible channel, the approach we use is to apply exponential fits to the time series of a chosen group of stars. Each exponential fit is of the form

$$Be^{-At} \ .$$

The time t is measured in days. The time $t = 0$ corresponds to the starting date of the time series. In the initial method, Method 1, an exponential model is constructed for a chosen star with all the available SNRs computed by the OATS, with only one important exclusion rule. The exclusion rule is that the star SNRs obtained within five hours on each side of the local midnight are not to be included. Signals measured in this period are usually low in value, due to distortion of the scan mirror caused by increased heating by the sun (see Bremer, et al.,[1] pp. 150–151). Aside from this local-midnight restriction, a signal is accepted as a sample for the time series. Figure 4 shows the plot of such a time series of SNRs of the star β-Cnc, together with the graph of the exponential fitting function. For each satellite, time series from approximately 40 stars are used to obtain an average A-coefficient. The average A-coefficients are posted on the web site given in Section 1. Table 2 gives a summary of such average degradation coefficients for GOES–8, –9 and –10.

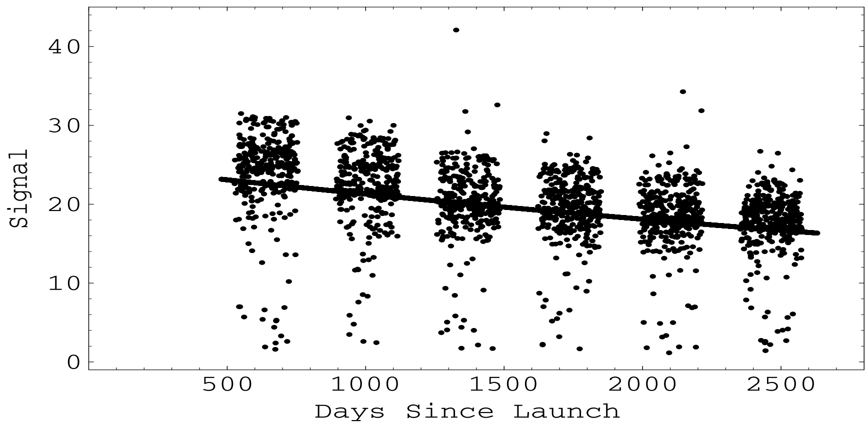

Figure 4. A time series of star signals of β-Cnc from GOES–10 and the exponential fit for this time series. The data selection method is Method 1. The method is applied to data obtained over the period October 7, 1998, to May 13, 2004. Each signal is a sum of SNRs that include the GAIN/NOISE factors. Each detector that registered star signals contributed an SNR to the sum. Day 1 is the launch date of GOES–10: April 25, 1997.

Table 2. Estimated degradation rates using Method 1. Each estimated rate $\hat{A}$ is the average of the A-coefficients of approximately 40 stars. The stated error is the usual standard error of the mean.

Spacecraft	**$\hat{A}$(annual rate)**	**Length of Time Series**
GOES–8	$4.96 \pm 0.09\%$	April 10, 1995 to April 1, 2003
GOES–9	$5.41 \pm 0.28\%$	August 7, 1995 to May 16, 1998
GOES–10	$5.96 \pm 0.07\%$	May 16, 1998 to May 13, 2004

Data used in Method 1 show a significant number of unusually high and low SNRs. After a period of investigation, we became certain that these outliers are the results of two causes. The low SNRs tend to be associated with star looks where the star image crossed over Detector 1 or Detector 8. These two detectors are the two end detectors in the array, and low signals may occur when part of the image passes below or above the array. Figure 5 shows a plot of results of star images crossing over Detector 1. The computed SNR from the OATS is 4.97. The SNR of the same star in a crossing over only one detector that is in the interior is usually in the range 8.0–12.0 for this period of observation. For instance, Figure 2 is a plot of signals from the same star detected on Detector 7 about 2 months earlier, with an SNR of 10.93.

The unusually high SNRs occur where the trajectory of the crossing spans more than one detector. In this case, the SNR computed by the OATS is the sum of the SNRs from all the detectors involved, which is the sum of several estimated peak signals, and hence usually higher than the actual peak signal of the star. One of the higher values in the data plot in Figure 4, for instance, is the star signal obtained on January 24, 2004 (Day 2466). Star detection occurred on Detector 2 and Detector 3 of GOES–10. The computed SNR is 24.82. This is significantly higher than the signals measured in star events where only one of the two detectors sighted the star. Such signals are all in the range of 13.0 to 18.5 during the two weeks about January 24.

Another factor in the OATS calculation of SNR that can unnecessarily scatter the computed SNRs is the multiplication of the detector dependent constant GAIN/NOISE in formula (1). The upper plot in Figure 6 is the time series for star β-Cnc computed from data of the visible channel of GOES–10 using formula (1). The data are chosen so that the star looks with multiple-detector crossing or boundary-detector crossing are not included. For

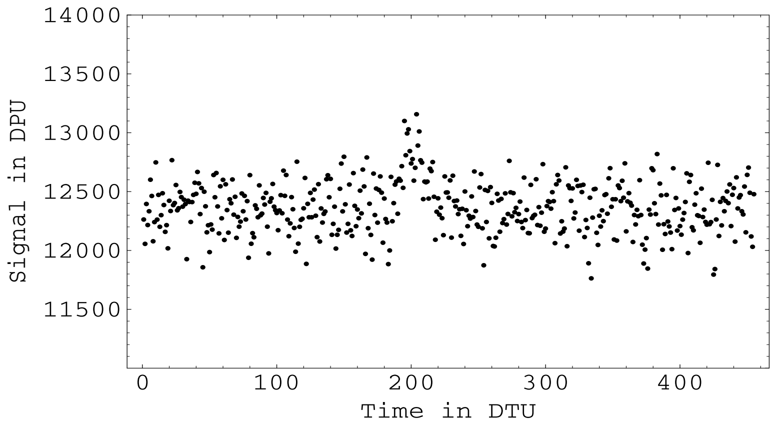

Figure 5. Weak star signals were registered in a crossing of δ-Eri over Detector 1. We infer that only a portion of the star image actually crossed over the detector.

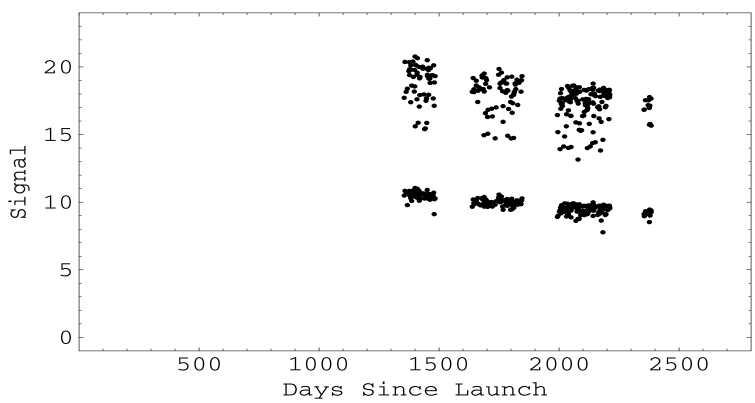

Figure 6. Removal of the Gain/Noise factors in the calculation of the SNRs of β-Cnc yielded a significantly more coherent time series (lower series). Data in the upper time series are SNRs computed by algorithms of the OATS from GOES–10 star measurements, over the period January 4, 2001, to November 2, 2003. With the GAIN/NOISE factors removed, the magnitude of an SNR in the lower time series is expressed in terms of the usual unit of DPU. On the abscissa, Day 1 is April 25, 1997, the launch date of GOES–10.

the same set of input data, if the calculation in formula (1) is made without having the factor GAIN/NOISE, the resulting SNRs show improved coherence. The lower plot of Figure 6 is a plot of such unweighted star SNRs. We interpret this finding as an indication that at least six of the eight detectors show responsivities that are highly similar. The inclusion of the normalization factors GAIN/NOISE leads to contrary and incorrect inferences.

Using the investigations and observations described above, we modified Method 1. Star looks involving Detector 1 or Detector 8 are rejected. Rejected also are all the star looks where the star image crossed over more than one detector in each star window of two or more consecutive star looks. Thus the admissible SNRs are all single-detector SNRs. Each such SNR was also divided by the appropriate GAIN/NOISE to remove the OATS-introduced influence of that factor. The resulting time series of the star SNR values almost always shows

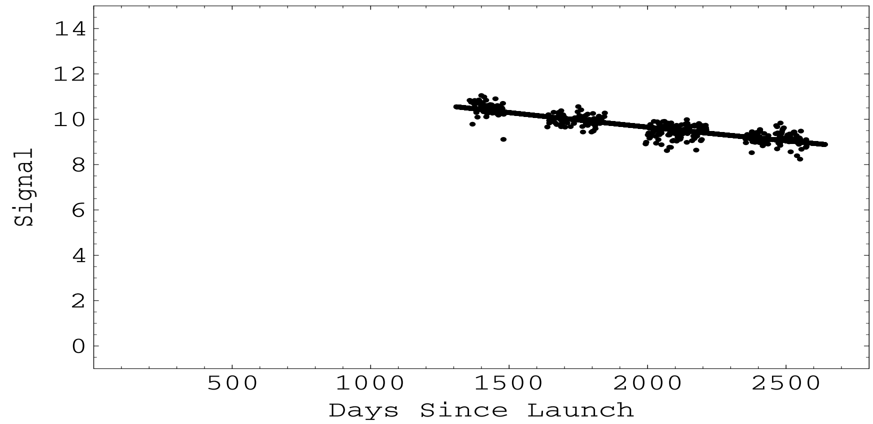

Figure 7. A time series of star signals of β-Cnc from GOES–10 and the exponential fit for this time series. The data selection method is Method 2. The method is applied to data obtained over the period January 4, 2001, to June 8, 2004. The signals are expressed in units of DPU. Day 1 is the launch date of GOES–10: April 25, 1997.

significantly less noise. Figure 4 and Figure 7 show a comparison of two time series for the star β-Cnc. The plot in Figure 7 is the result of applying the several selection criteria to the portion of data used in Figure 4, starting from January 4, 2001. The selection methods cannot be applied to the data that precede the date because information on the detector-by-detector activities in those star looks is not yet available.

We point out here also that in Method 2 we selected stars with more attention given to excluding those whose brightnesses might vary over the period of the time series. In addition, we selected stars only with intensities of 5.0 or more, and having 100 or more screened samples in the time series. Table 3 shows trending results using Method 2.

Table 3. Estimated degradation rates using Method 2. Each estimated rate $\hat{A}$ is the average of the A-coefficients of approximately 60 stars. The stated error is the usual standard error of the mean.

Spacecraft	**$\hat{A}$(annual rate)**	**Length of Time Series**
GOES–8	$4.86 \pm 0.08\%$	October 19, 1995 to April 1, 2003
GOES–10	$4.95 \pm 0.11\%$	January 4, 2001 to June 8, 2004

4. LIMITATIONS OF THE STAR VICARIOUS CALIBRATION METHODS

This technique of trending star signals is based on the irradiance of a point source rather than the radiance of an extended source. Therefore, a star trend may be slightly different from a trend seen on Earth scene.

Although the detectors used for Earth imaging are the same as those used for star observation, the star observations employ an additional stage of amplification in the electronics. We believe, but cannot be certain, that the gain of the additional stage is constant in time.

Star sense methods are providing several stable long-term estimations of the degradation rates of the visible channels of the GOES satellites. The results, however, have not been used so far for absolute calibration of a visible channel. This would require geometric analyses to convert irradiance to radiance. It may be more

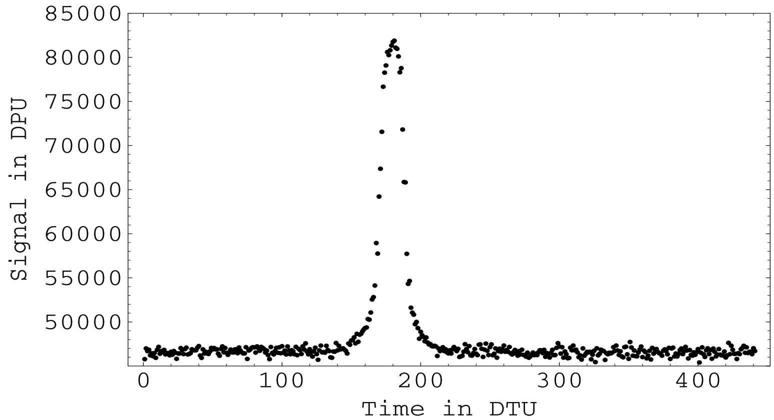

Figure 8. A plot of a composite profile for the star crossing of β–Ori in Figure 3. The profile (signal versus time) is the sum of the four profiles in Figure 3.

practical to render the calibration absolute by tying the time series to an absolute calibration from another technique, such as intercalibration with NASA's Earth Observing System (EOS) Moderate Resolution Imaging Suite (MODIS).[2]

5. FURTHER DEVELOPMENT IN STAR-SIGNAL MONITORING

Star looks where a star trajectory crossed over more than one detector, not including Detector 1 or Detector 8, have been excluded from Method 2. Such star looks usually occur when brighter stars are sensed. Thus brighter stars have mostly been excluded from contributing to the monitoring of responsivity. But the brighter stars are strong candidates for providing steady light sources for monitoring the integrity of a detector. A procedure is currently planned to include such star looks in the construction of the signal time series of a star. In this procedure, we regard the six interior detectors consisting of Detector 2 to Detector 7 as a single (larger) detector. At each instant of a star observation, each signal pixel used in the calculation of the SNR is the sum of the superpixels contributed by the detectors that registered star sighting. For the star crossing given in Figures 3 in Section 2, the sum of the four signal profiles is given in Figure 8. The SNR is now computed by estimating the peak value of the composite profile. We expect the inclusion of this procedure will improve further the reliability of the trending functions.

REFERENCES

1. Bremer, J.C., J. G. Baucom, H. Vu, M. P. Weinreb, and N. Pinkine, "Estimation of long-term throughput degradation of GOES 8 & 9 visible channels by statistical analysis of star measurements," in *Earth Observing Systems III*, *Proc. SPIE* **3439**, pp. 145–154, 1998.
2. Wu, X., "Post-launch calibration of GOES Imager visible channel using MODIS," to appear in *Proc. ISSSR'03*, 2003.